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Enterprise level maintenance strategy selection an empirical model

Joseph Virgil Amalesh
University of Tennessee

To the Graduate Council:

I am submitting herewith a thesis written by Joseph Virgil Amalesh entitled "Enterprise level maintenance strategy selection an empirical model." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Rapinder Sawhney, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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We have read this thesis and recommend its acceptance:

Dr.Xueping Li

Dr.Ramon Leon

Accepted for the Council:

Carolyn R. Hodges
Vice Provost and Dean of the
Graduate School

(Original signatures are on file with official student records.)

Enterprise Level Maintenance Strategy Selection: An Empirical Model

A Thesis
Presented for
the Master of Science
Degree
The University of Tennessee, Knoxville

Joseph Virgil Amalesh
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Abstract

Maintenance plays a significant role in increasing the overall profit of an organization. However, the lack of efficient maintenance strategy selection procedures causes the operating costs to increase thereby decreasing the organizational profit. A review of the commonly used maintenance strategy selection models shows that the cost of maintenance is not considered during maintenance strategy selection. This thesis proposes an empirical approach for selecting maintenance strategies based on the economic impact of the strategy on the organizational profit. The Enterprise Level Maintenance Strategy Selection (ELMSS) model proposed in this thesis calculates the total maintenance lead time (TMLT) and total maintenance cost (TMC) of the equipment by simulating the system under different maintenance strategies and breakdown conditions. The simulated values are then used for calculating the profit associated with different maintenance strategies. The mean profits associated with each strategy are then tested for its statistical significance and the strategy that generates the highest profit is selected as the best strategy. Finally, the selected strategy is validated by simulating the system and comparing the process metrics with the existing metrics. The methodology also gives a crude estimate of the optimal maintenance scheduling time that will aid in maximizing the profit.

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Chapter 1

Introduction

Chapter 1 provides a description of the maintenance issues most manufacturers face within the current times of economic downturn. Maintenance has been dealt by most manufacturers as a tactical issue which now needs a more strategic approach, an approach that links the need for maintenance strategy to the enterprise health. This chapter states the relevance of the problem which outlines the objective of this research. An outline of the proposed Enterprise Level Maintenance Strategy Selection (ELMSS) model is given in this chapter. The chapter also gives an overview of the organization of this thesis.

1.1 Introduction

The events on Wall Street in the recent times have made it clear that we live in a global environment in which companies impact supply chain regardless of geography or culture. Yet organizations expect maximum returns for their continued investment. There are many avenues and different strategies to maximize profits. One dimension of increasing profits within the manufacturing environment is World Class Manufacturing. In order to increase the overall profit, companies increase productivity and reduce costs by focusing on quality, on time delivery and cost.

One of the critical components that affect production is maintenance [1]. Maintenance strategies reduce the need for capital due to increased equipment life and equipment availability. A maintenance strategy can also impact the quality of the product and the ability of the manufacturer to deliver products on time. On the other hand poor maintenance performances can propagate to excessive costs such as warranty costs, overtime costs and capital expenditure costs. Increasing the production capacity and capability without excessive costs is the business goal of maintenance. This requires organizations to optimize their ability to leverage maintenance (right time, right duration) resources.

In the manufacturing environment maintenance is considered as a secondary input for production [2]. Automation and enhanced technology has shifted production processes from humans to machines. This has placed the importance of equipment on par with the ability to use human resources to meet increasing customer expectation. Therefore maintenance must be viewed as a production strategy rather than an overhead cost, as maintenance costs are becoming a larger portion of the total budget. US manufacturers allocate about $500 -700 billion per year for maintenance [3]. Figure 1 highlights the cost and payback for maintenance verses the company cost [4]

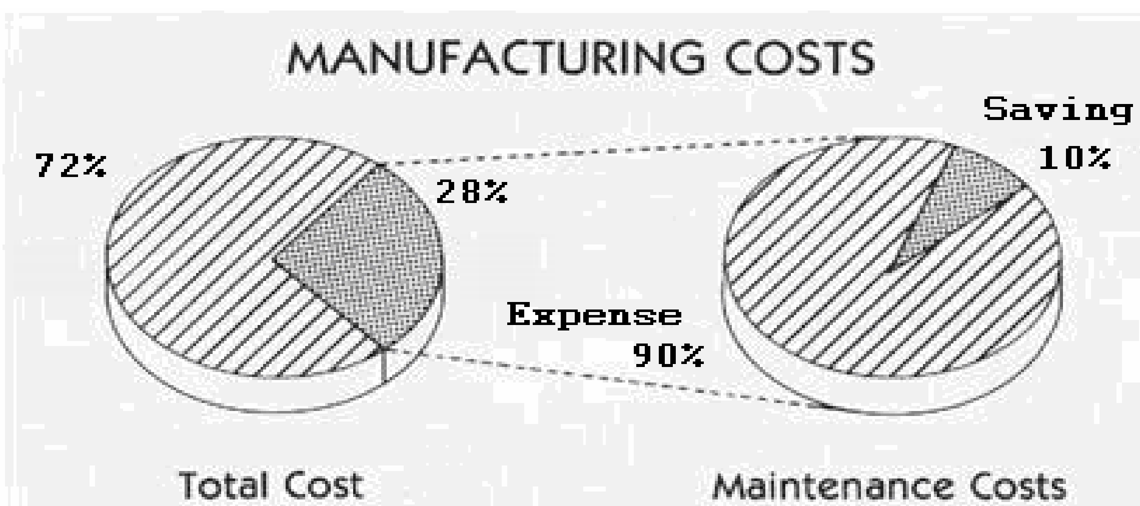

Figure 1: Maintenance Cost versus Company Cost

Table 1: Maintenance Cost as a Percent of Total Cost by Industry Sector

Industry Sector	Maintenance Cost (%)
Mining	20 to 50
Primary Metal	15 to 25
Manufacturing	5 to 15
Processing	3 to 15
Fabrication and Assembly	3 to 5

Table 2: Maintenance Coat as a percent of Total Sales by Industry

Industry Sector	Maintenance Cost (%)
Automotive	6
Chemical Processing	8
Electronics	3
Fabricated Metals	5
Machine Tool	5
Paper and Pulp	9
Petroleum Production	9
Rubber/Plastics	7

Table 1 shows the percentage of maintenance cost as a function of the total production cost and Table 2 shows these costs for different industries [5]. It is estimated that around $100-200 billion dollars can be saved if advanced maintenance and reliability technologies could be developed and implemented [3]. As a consequence of this huge cost saving, maintenance department in most of the manufacturing facilities have become a high-level business unit. Production and capital expenditures can be greatly reduced through improved maintenance procedures. A study conducted by the Electric Power Research Institute (EPRI) during 1981-1988 on Operation and Maintenance (O&M) costs of nuclear power units showed that the O&M costs increased at the rate of nine percent per annum [6]. The study further emphasized the need for optimizing the overall process of maintaining and operating plants and adopting new technologies in order to reduce the O&M cost. In the United States, 20% of the total electric energy is generated by nuclear plants and ironically these plants spend 30% of their total energy generation cost in O&M of the plant.

The aforementioned reports on the cost of maintenance forces management personnel to consider maintenance as an expense rather than perceiving it as a profit. However, the fact that maintenance cost represent up to 15% of the total value-added costs [7] and that maintenance costs are 3%-6% of the replacement cost of a plant [8] may provide most management with a shock and an incentive to re-evaluate their paradigm for maintenance and emphasize the need for a maintenance strategy that balances the cost of downtime due to maintenance with the cost of resources allocated to maintenance.

1.2 Problem Statement

Improper maintenance of plant equipment can significantly increase the overall operating cost due to production losses and unplanned intervention on the system. As a consequence the return on net assets (RONA) of the organization is considerably reduced. The best way to improve asset productivity and reduce the cost of downtime is to implement an effective maintenance strategy that will aid the organization to generate maximum profits with its available assets. Strategies that reduce equipment downtime might not necessarily increase the organizational profit due to the high costs associated with performing the maintenance operation. Similarly strategies that are cost effective may also not maximize the profit due to the high maintenance lead time which reduces the equipment productivity. Figure 2 depicts the problem involved in selecting an optimum maintenance strategy. From this figure it can be seen that strategies that aim at reducing equipment breakdowns by performing maintenance at frequent intervals tend to reduce the maintenance cost, however it does not increase the organizational profit due to the low equipment availability which results in reduced production. On the other hand, strategies that focus on increasing the equipment availability by increasing the frequency of maintenance tend to reduce the organizational profit due to the high cost associated with the maintenance. Hence an optimal maintenance strategy should be selected that maximizes the organizational profit by optimizing the equipment availability and cost of maintenance.

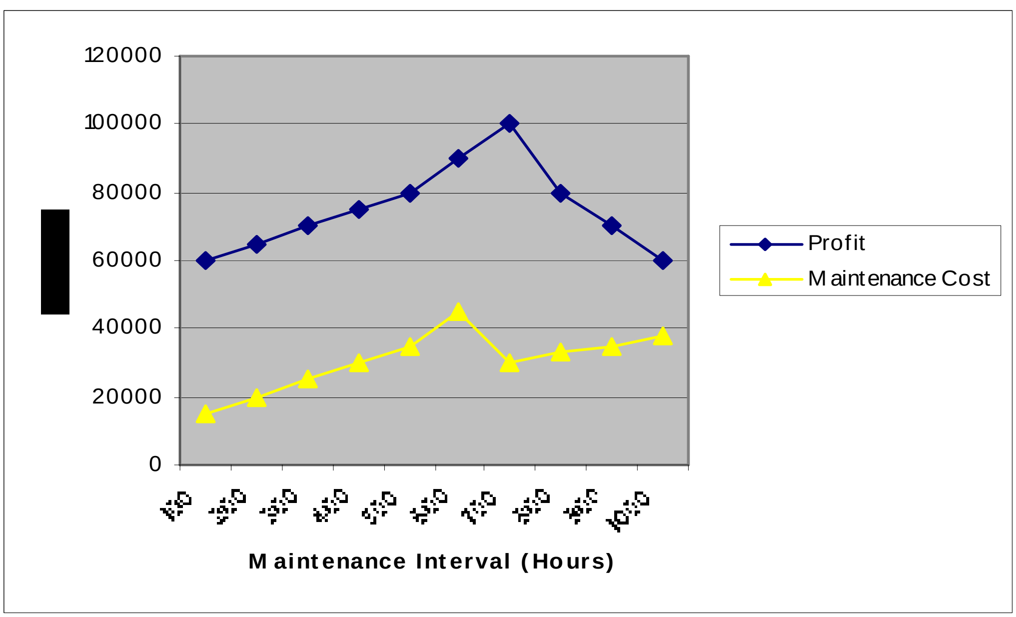

Figure 2: Problem Statement

To address this issue the following objectives are proposed in this thesis

- Develop a methodology to determine the critical process metrics
- Develop a analytical model for strategy selection based on the defined critical process metrics
- Develop a user interface platform to simplify the maintenance strategy selection process

1.3 General Approach

The general approach that will be followed in this thesis for selecting the best maintenance strategy consists of five phases as shown in Figure 3. The Critical Component Identification phase involves identification of the components that are critical for the operation of the equipment. In this phase a modified Failure Mode Effect and Criticality Analysis (FMECA) approach is used for identifying the critical components. The mean time to failure (MTTF) and mean time to repair (MTTR) of the critical components identified in the first phase are used for calculating total maintenance lead time (TMLT) and total maintenance cost (TMC) of the equipment in the Simulation phase. In this phase the components are simulated under different maintenance strategies and the corresponding TMLT and TMC are calculated. The simulated values are then used in the Profit Calculation phase for calculating the mean profit associated with each strategy. In this phase a Microsoft EXCEL based deterministic model is used for profit calculation. The statistical significance of the calculated profits is also determined in this phase. In the Strategy Selection phase, a comparative analysis is performed on all the

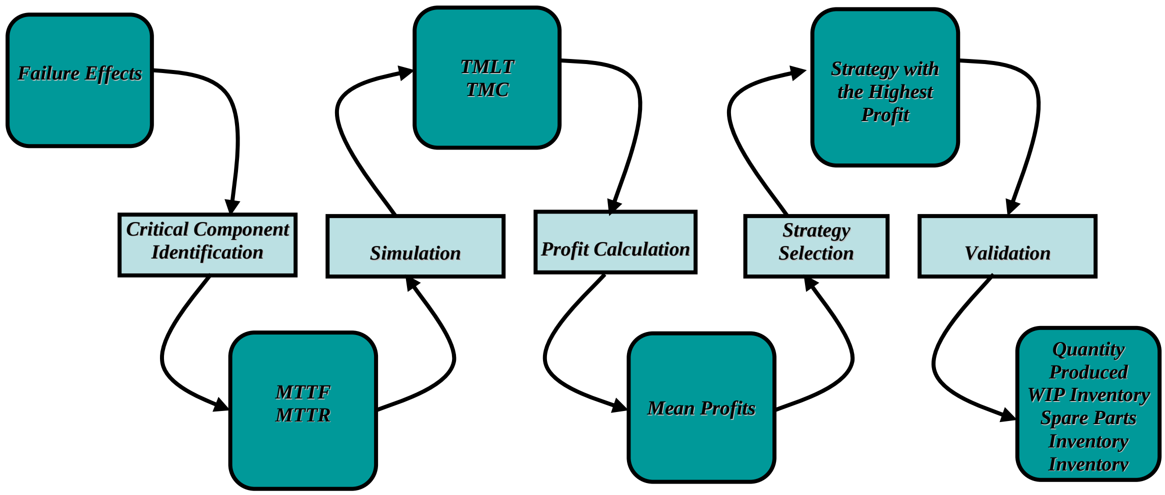

Figure 3: General Approach

strategies and the strategy that has the highest mean profit with the minimum variation is selected as the best maintenance strategy. Finally, the selected strategy is validated in the Validation phase. In this phase the performance associated with the selected strategy is compared with the metrics of the existing strategy. The validity of the ELMSS model is tested in this phase by comparing the features of the ELMSS model against other existing maintenance strategy selection models defined in the literature review. Table 3 shows the metrics used for the ELMSS model.

1.4 Organization of Thesis

The thesis is organized into five chapters which includes this introductory chapter. Chapter 2, "Literature Review", gives a brief introduction to industrial maintenance and the various maintenance policies that are commonly practiced. It provides a comprehensive review of the tools and techniques that are used for maintenance strategy

Table 3: Metrics used in the Model

Phase	**Input**	**Output**
Critical Component Identification	Failure Modes Failure Effects	MTTF MTTR
Simulation	MTTF MTTR	TMLT TMC
Profit Calculation	TMLT TMC	Mean profits associated with each strategy
Strategy Selection	Mean profits associated with each strategy	Strategy with the highest profit and minimum variation
Validation	Strategy with the highest profit and minimum variation	Quantity Produced Work In Process Inventory Spare Parts Inventory Inventory Holding Cost

selection. Chapter 3, “Methodology”, gives a general description of the methodology proposed in this thesis. Chapter 4, “Case Study and Results”, illustrates the application of the proposed methodology using a case study and analyses the results obtained from the case study and discusses the validity of the model. Chapter 5 “Conclusion”, summarizes the major conclusions of this thesis. It gives the various merits and demerits of the methodology and discusses the opportunities for improving the model and the scope for future research in this area.

Chapter 2

Literature Review

Chapter 2 provides a brief introduction to industrial maintenance and the various maintenance policies that are commonly practiced. It provides a comprehensive review of the current models and its associated tools that are used for maintenance strategy selection.

2.1 Introduction to Maintenance

Maintenance is defined as the sequence of activities required to keep an item in, or restore it to, a state in which it can perform its intended function [9]. Its primary purpose is to maximize the availability of production systems at the most minimal cost [10]. On the contrary maintenance costs accounts for 15 to 40% of the total production cost [11]. Due to the high cost and low efficiency associated with maintenance, it has become a common item on the hit list of many cost-reduction programs [12]. However in the modern manufacturing environment, increase in automation and the importance of performance and profitability of manufacturing systems has made maintenance a major profit-generating business element [13]. Many industries are beginning to consider maintenance as an essential component of the operating budget. With asset availability and reliability playing a crucial role in determining the success of an organization, maintenance can help in improving the competitiveness of capital investment organization [14].

Some of the major issues that challenge maintenance operations are quality improvement, cycle time, set-up time, cost reductions, capacity expansion and related environmental issues [15]. Emerging trends of operation strategies, toughening societal expectations and the technological advancements have made the performance demanded of maintenance even more challenging [13]. A key solution to overcome these challenges is to have a well planned maintenance strategy. The demand for higher uptime and reduction of adverse effects of a breakdown has made many manufacturers to adopt a maintenance strategy that will maximize productivity and minimize the associated cost.

2.2 Classification of Maintenance

In general, maintenance is classified as either planned or unplanned. Based on the degree to which the operating condition of the equipment is restored, maintenance is classified into the following types [16],

2.2.1 Perfect Maintenance

It is the activity that restores the operating condition of an equipment to as good as new.

2.2.2 Imperfect Maintenance

It is the opposite of perfect maintenance, wherein the system is not restored to a new condition but it is restored to a condition which is in-between old and new.

2.2.3 Minimal Maintenance

It restores the equipment to a condition at which its failure rate is similar to the rate that the equipment had when it failed.

2.2.4 Worse Maintenance

It increases the failure rate of the system but does not cause the system to breakdown.

2.2.5 Worst Maintenance

It is the activity that causes a system to breakdown.

2.3 Trends in Maintenance

In the recent years, there has been a considerable change in maintenance trends. One of the major reasons for this drastic change is the level of importance given to maintenance. Figure 4 shows the different trends in maintaining equipment over the past 75 years.

Some of the most important areas of change that have occurred in the field of equipment maintenance over the past 15 years are as follows [17]

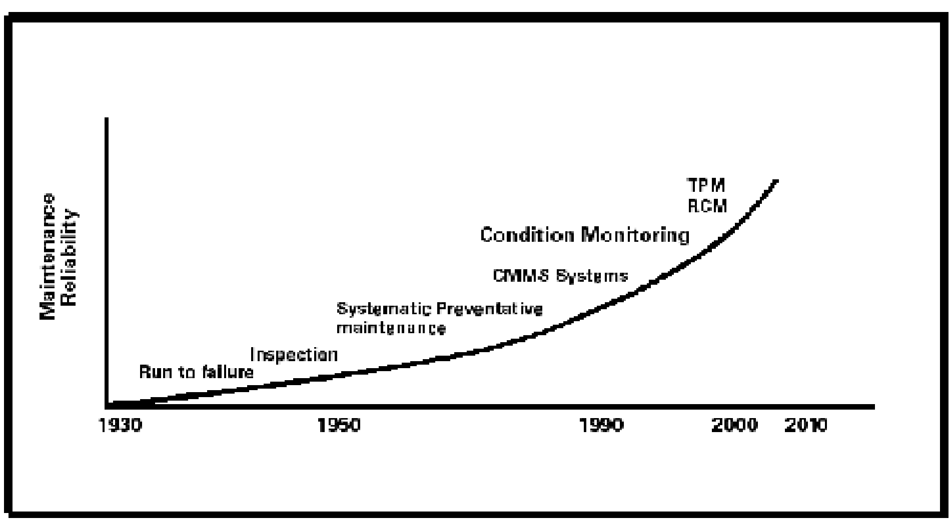

Figure 4: Trends in Maintenance

- *Objective of Maintenance*

The primary objective of maintenance has changed from just optimizing plant availability at minimum cost to optimizing all the aspects of business effectiveness and safety, environmental integrity, energy efficiency, product quality and customer service. Also, the focus of maintenance has changed from preserving physical assets to preserving the function of the assets.

- *Frequency of Maintenance*

In the past maintenance activities were scheduled with the aim of preventing the failures. However in the current trend the main focus is on avoiding, reducing or eliminating the consequences of failures.

- *Types of Maintenance*

Traditionally, Preventive, Predictive and Corrective maintenance were considered to be the three basic types of maintenance policies. In the current trend, Reliability Centered Maintenance is also considered as one of the basic maintenance policies.

- *Failure and Maintenance*

The fact that most equipment tend to fail as it gets older has always been in the past. However the current fact is that effective maintenance policies help in making the failures not to occur immaterial of the age of the equipment.

- *Development of Maintenance Program*

  The trend of developing a maintenance program by the maintenance department has changed to a new trend of developing maintenance programs by maintenance personnel and equipment operators

- *Solving Maintenance Problems*

  The old method of finding a quick, one-shot solution to all maintenance problems is replaced by a new methodology which has two stages. In the first stage the thinking process of the people is changed and in the second stage their thought process is applied to the actual problem.

2.4 Maintenance Strategies

A system can be made highly reliable, readily available and ensured with good safety performance measures at the lowest possible cost if the appropriate maintenance strategy is selected [16]. A lot of research has been carried out in the area of maintenance strategy selection in order to prevent the occurrence of system failure and improve system availability. Traditionally, reactive maintenance was the only strategy that was followed by most companies [18]. This involved fixing machines only when they stopped working. Technological advancements and sophistication of maintenance personnel paved the way for a different type of strategy known as proactive maintenance wherein a combination of preventive and predictive maintenance activities are utilized for preventing failures. More recently a new type of strategy called aggressive maintenance is practiced in some industries. One of the aggressive strategies is the Total Productive Maintenance which focuses on the production equipment design and performance improvement [18]. A detailed description of each of the maintenance strategies is given below.

2.4.1 Reactive Maintenance Strategy

In this strategy a maintenance operation is performed on equipment only after the equipment has actually failed. It is also known as a “fire-fighting” approach [19]. Temporary repairs are performed on the equipment to bring it back to the operating condition and a permanent solution to the problem may be made some time later [20]. This reduces the manpower and cost involved in maintenance [21]. However this approach may make the production capacity highly fluctuating and increase the maintenance cost in the event of some major catastrophic failure [20, 22].

2.4.2 Proactive Maintenance Strategy

The main objective of proactive maintenance strategy is to reduce the probability of unexpected equipment failures. The activities of this strategy involve performing maintenance operations after a specific period of time or amount of machine use [22,23] as well as performing maintenance in response to a specific equipment condition [21,22]. Proactive maintenance strategy ensures extended equipment life and reduced maintenance cost. However, impediment to the production work due to maintenance operation is one of the major disadvantages of this maintenance strategy.

2.4.3 Aggressive Maintenance Strategy

The primary objective of aggressive maintenance strategy is to improve the overall equipment operation through improved equipment design. In this strategy, the maintenance department and the engineering department work together in designing the equipment with the idea of making operation and maintenance as easy as possible [24,25]. This helps the team to determine the reasons of failure and provide appropriate solutions for it [26, 27]. Aggressive maintenance strategy ensures increased equipment availability and reduced maintenance cost.

2.5 Current Maintenance Practices

In the manufacturing environment, maintenance stratgies are composed a combination of maintenance practises. Some of the commonly followed maintenance practises are ;

2.5.1 Corrective Maintenance (CM)

Corrective maintenance which is also known as reactive maintenance is performed on equipment only after the occurrence of a failure.

2.5.2 Preventive Maintenance (PM)

Preventive maintenance involves activities that are performed on equipment at regular, pre-specified intervals or other prescribed criteria to ensure that the equipment is brought back to its operating condition. It is also known as periodic or time based maintenance.

2.5.3 Predictive Maintenance (PdM)

Predictive maintenance which is also known as condition based maintenance monitors the performance parameters of equipment continuously and comparers it with established engineering limits. This helps in determining the type of action that is needed bring the equipment back to its operating condition

2.5.4 Reliability Centered Maintenance (RCM)

Reliability Centered Maintenance determines the maintenance required for equipment using a decision logic tree which takes into consideration the safety and operational consequences of each failure and the degradation mechanism responsible for the failure.

2.6 Maintenance Strategy Selection Methods

The methods by which maintenance strategies are selected depends upon a number of criteria's, namely the type of equipment, maintainability of the equipment, cost effectiveness, time of selection i.e. design phase or operation phase, the level of selection i.e. national or company-wide, plant, system, unit or component level and also the level of people who make the decision i.e. maintenance department or top level management. Every method has its own method of selecting the best maintenance strategy. Some of the features that are considered to be ideal for a maintenance selection method are [29],

- Ability to be used across all maintenance approaches
- User friendliness
- Utilizing personnel knowledge and experience

- Considering financial aspects adequately and consistently
- Considering technical analysis before data gathering
- Ability to consider organizational aspects
- Ability to measure cost effectiveness
- Ability to consider the plant holistically

2.7 Overview of Maintenance Strategy Selection Models

The greatest difficulty in selecting the best maintenance strategy for a manufacturing system is, understanding the large number of tangible and intangible attributes such as safety aspects, environmental problems, cost, budget constraints, manpower utilization, Mean Time Between Failure (MTBF) and Mean Time Between Repair (MTBR) for each piece of equipment [30]. The following section gives an overview of the various models that are used for selecting maintenance strategies

2.7.1 Optimization Models

In 1998, Decker and Staff stressed the necessity of a new information technology tool in the area of maintenance decision making [28]. They give a detailed review of the various maintenance optimization models and the ways in which the models can be applied for maintenance optimization. Maintenance optimization is the process of determining the optimum balance between the costs and benefits of maintenance while taking the maintenance resources and requirements into consideration [31]. The goal of the maintenance optimization process is to select the appropriate maintenance technique for each piece of equipment within a system that will increase the equipment reliability, availability, productivity and reduce the cost associated with performing the maintenance operation. If implemented effectively, maintenance optimization will result in

- System Availability Improvement
- Equipment Reliability Improvement
- Overall Maintenance Costs Reduction
- System Safety Improvements

A true maintenance optimization process continually monitors and optimizes the current maintenance program to improve its overall efficiency and effectiveness. In order for the optimization process to sustain extra efforts have to be taken such as removing unnecessary requirements, identifying adverse failure trends, conducting root-cause analysis of component failures resulting in system events, reporting maintenance feedback, conducting predictive maintenance analysis, monitoring system performance, trending preventive maintenance and corrective maintenance historical data, conducting surveillance test optimization studies, introducing equipment design modifications.

Maintenance optimization models widely include linear and nonlinear programming, dynamic programming, Markov decision methods, decision analysis techniques, search techniques and heuristic approaches. In general, maintenance optimization models cover four aspects:

1) Description of a technical system, its function and its importance

2) Modeling of the deterioration of the system in time and possible consequences for the system

3) Description of the available information about the system and the actions open to management

4) Objective function and an optimization technique which helps in finding the best balance.

Based on the way deterioration is modeled into the system, Sherif & Smith [32] classified the maintenance optimization models into:

1. Deterministic Models
2. Stochastic Models
    a. Under Risk
    b. Under Uncertainty.

Marseguerra and Zio illustrated the use of genetic algorithm and Monte Carlo simulation for optimizing maintenance and repair policies [33]. Blundell developed maintenance developed optimization models for selecting maintenance strategies for aero engines [34]. The results of maintenance optimization models are varied. Different policies can be evaluated and compared with respect to cost-effectiveness and reliability characteristics. It is also possible to obtain results based on the structure of optimal polices, like the existence of an optimal control-limit policy. Also, models can assist in determining the frequency of maintenance. Finally, models can also be used to determine the effectiveness and efficiency of schedules and plans, taking all kind of constraints into consideration.

2.7.2 Multi Criteria Decision Making (MCDM) Models

MCDM is the process of selecting the best alternative from a finite set of alternatives that have conflicting evaluations. The process involves ranking of the alternatives based on a finite set of criteria, weighted according to their importance. The evaluation ratings are, then, aggregated taking into account the weights of the criteria, to get a global evaluation for each alternative and a total ranking of the alternatives. There are several methods used for decision making such as simple additive weighting (SAW), multiplicative exponential weighting (MEW), and technique for order preference by similarity to ideal solution (TOPSIS), and the analytic hierarchy process (AHP). Also, many useful fuzzy MCDM methods have been developed. The use of Analytical Hierarchy Process (AHP) as a multi criteria decision tool for maintenance strategy selection was first explained by Almedia and Bohoris [35]. Bevialqua and Broaglia illustrated the application of AHP technique for maintenance strategy selection in an Italian Oil Refinery processing plant using economic factors, applicability, cost, safety, etc as the criteria for decision making [36]. Bertolini and Bevilacqua later developed a methodology that combines Lexicographic Goal Programming and AHP in selecting the best maintenance strategies for critical centrifugal pumps in an oil refinery [30]**.** Al-Najjar and Alsyouf used a fuzzy MCDM technique for identifying the failure causes of roller element bearings in a paper industry [37].

2.7.3 Management Models

The widely used management models for maintenance strategy selection are RCM methodology, Total Productive Maintenance (TPM) and FMECA technique. The RCM methodology involves selecting the maintenance strategy that minimize maintenance costs by balancing the higher cost of corrective maintenance against the cost of preventive maintenance, taking into account the loss of potential life of the unit in question [38]. Jesse developed a hybrid of an RCM approach and Asset Life-Cycle Analysis technique for selecting a suitable maintenance strategy for wind turbines [39]. TPM is a new way of looking at maintenance, or conversely, a reversion to old ways but on a mass scale. In TPM the machine operator performs much, and sometimes all, of the routine maintenance tasks themselves. One way to think of TPM is "deterioration prevention" and "maintenance reduction", not fixing machines. For this reason many people refer to TPM as "Total Productive Manufacturing" or "Total Process Management". TPM is a proactive approach that essentially aims to prevent any kind of slack before occurrence. Its motto is "zero error, zero work-related accident, and zero loss." The FMECA technique selects the best maintenance strategy by analyzing the severity and probability of the failure modes and selects the strategy that reduces the severity and probability of the failure modes [40].

2.7.4 Cost Effective Models

Cost effective maintenance selection models improve the quality, efficiency and effectiveness of a company’s operation [41]. As a consequence the company will experience productivity advantages, value advantages and long-term profitability. Making a cost-effective maintenance decision is not an easy task, especially when the production system consists of several different components with different maintenance characteristics and the maintenance program must combine technical requirements with the firm's managerial and business strategies. Al-Najjar, Alsyouf and Ingwald developed a practical model for selecting and improving the most cost-effective maintenance policy [29]. Alsyouf developed a cost effective maintenance strategy selection model to illustrate the role of cost effective maintenance in achieving competitive advantages [41]. He developed the model by studying the current maintenance practices in the Swedish industry and the methods by which the strategies are selected and incorporating all the strengths of the selection methods into his model.

2.7.5 Simulation Models

There is very less work done in the area of maintenance strategy selection using simulation models. Some of the related works include the simulation model developed by Contreras, Modi, Pennathur for selecting best maintenance strategy in a distribution warehouse using the failure data obtained from for motors and gearboxes [42]. Dessouky and Bayer used a simulation and design of experiments approach for selecting maintenance strategies for maintaining buildings [43]. Vasanth developed a simulation based approach to aid manufacturers in selecting a cost effective maintenance strategy by integrating reactive and proactive maintenance [44].

Table 4 provides a summary of all the maintenance strategy selection models discussed in this chapter and Table 5 summarizes the various publications in the area of Maintenance Strategy Selection Models. A review of the existing maintenance strategy selection models shows that none of these models consider the impact of maintenance cost on the organizational profit during maintenance strategy selection. This presents the uniqueness of this thesis, wherein an Enterprise Level Model is developed for considering the cost of maintenance during the maintenance strategy selection process.

Table 4: Comparison of Maintenance Strategy Selection Models

Models	Function	Strengths	Weaknesses
Optimization Models	Selects the appropriate maintenance technique for each piece of equipment within a system that will increase the equipment reliability, availability, productivity and reduce the cost associated with performing the maintenance operation.	Quantitative way of decision making Reduces uncertainty in decision making	Difficult to understand and to interpret. Requires mathematical knowledge
Management Models	Selects the strategy that reduces the severity and probability of the failure modes.	Systematic review of the process Wide range of errors can be evaluated	Not very effective in describing the system's reliability and safety Time consuming
Cost Effective Models	Selects the maintenance strategy that improves the quality, efficiency and effectiveness of a company's operation.	Easy to understand and interpret	Requires mathematical knowledge Does not consider the organizational aspects
MCDM Models	Selects the best maintenance technique from a finite set of alternatives that have conflicting evaluations	Straightforward and deterministic approach to select alternatives Does not require mathematical knowledge	Uncertainty in the decision making process Probability of rank reversal

Simulation Models	Selects the maintenance strategy that increases the availability, reliability, productivity and reduces the maintenance cost by performing a real time analysis of the system under various maintenance strategies.	Easy to understand and interpret Systematic review of the process	Requires programming knowledge

Table 5: Publications in Maintenance Strategy Selection Models

MSS Models	**Authors**	**Paper**
Optimization Models	1. M.Marseguerra et al [33] 2. Blundell et al [34]	Optimizing maintenance and repair policies using a combination of genetic algorithms and Monte Carlo simulation Maintenance strategies for aero engines.
MCDM Models	1. Bertollini et al [30] 2. Almeida AT et al [35] 3. Bevilacqua M [36] 4. Al-Najjar et al [37]	A combined goal programming-AHP approach to maintenance selection problem. Decision theory in maintenance decision making The analytic hierarchy process applied to maintenance strategy selection Selecting the Most Efficient Maintenance Approach using Fuzzy Multiple Criteria Decision- Making
Management Models	1. Crocker. J et al [38] 2. Andrawus, Jesse A et al [39] 3. Gilchrist W et al [40]	Age-related maintenance versus reliability centered maintenance: a case study on aero-engines The Selection of a Suitable Maintenance Strategy for Wind Turbines Modeling failure modes and effects analysis
Cost Effective Models	1. Imad Alsyouf et al [41] 2. Al-Najjar et al [29]	Cost Effective Maintenance for Competitive Advantages A Practical Model for Selecting and Improving the Most Cost-Effective Maintenance Policy

Simulation Models	1. Contreras LR et al [42] 2. Y.Dessouky et al [43] 3. Sawhney et al [44]	Intergrating Simulation Modeling and Equipment Condition Diagnostics for Predictive Maintenance Startegies. –A Case Study A simulation and design of experiments modeling approach to minimize building maintenance cost A Simulation Based Approach for Determining Maintenance Strategies

Chapter 3

Methodology

Chapter 3 illustrates the methodology involved in the maintenance strategy selection process. The chapter gives a detailed description of the various phases of the model which includes identifying critical components, simulation, profit calculation, strategy selection and validation. The MTTF of critical components that are determined in Phase 1 is used for calculating TMLT and TMC in Phase 2. The TMLT and TMC calculated in Phase 2 are then used in Phase 3 for calculating the profit associated with each strategy. 3. In phase 4, a comparative analysis is performed on all the strategies and the strategy that has the highest mean profit with the minimum variation is selected as the best maintenance strategy. Finally, the selected strategy and the ELMSS model are validated in phase 5. Figure 5 illustrates the ELMSS model in detail.

3.1 Identifying Critical Components

In this phase, components that are critical for equipment operation are identified by performing a FMECA on the individual equipment. In addition to identifying the potential failure modes and effects using the traditional FMECA approach, a modified

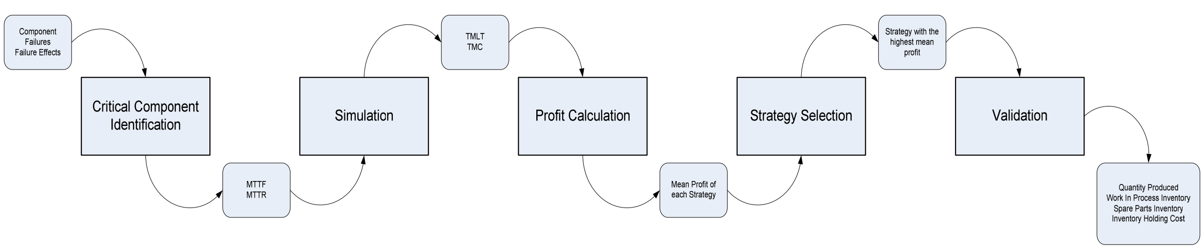

Figure 5: ELMSS Model

FMECA is proposed in this thesis which includes calculation of the MTTF and MTTR of each component. The procedure for determining the critical equipment components using the modified FMECA consists of two stages. The first stage involves data collection followed by ranking of the components based on their criticality in the second stage. A detailed description of the process involved in the two stages is given below. Figure 6 shows the input and output of phase 1.

Stage 1: Data Collection

In this stage, the components of each equipment are thoroughly analyzed and information related to their failure causes and effects are collected. As a first step in collecting component related information, a block diagram of the equipment is developed for understanding the structure of the equipment and the relation between the components that make up the equipment. The block diagram is then used for creating a FMECA worksheet for collecting component information such as function, failure causes, potential failure effects and the severity of the failure. In addition to this the MTTF and MTTR of the components are calculated in this stage. This involves determining the

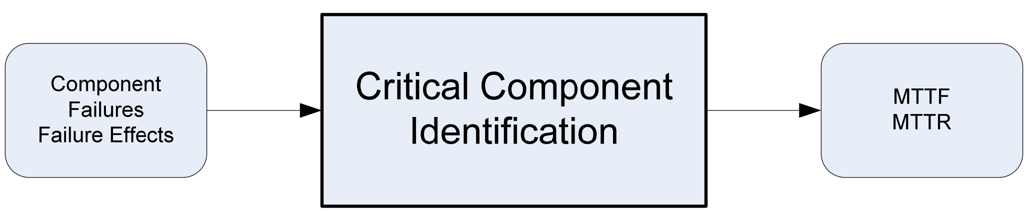

Figure 6: Phase 1

Table 6: Modified FMECA Worksheet

Component	**Function**	**Failure Cause**	**Potential Effects**	**Severity**	**MTTF (Hours)**	**MTTR (Hours)**

distribution the component failure times and repair times. The mean values of the corresponding distributions are then used as the MTTF and MTTR of the components in the subsequent phases. Table 6 shows a sample of the modified FMECA worksheet. The information in the FMECA worksheet is then used for identifying the components that are critical for the operation of the equipment.

Stage 2: Component Ranking

In this stage, the information collected using the FMECA worksheet is used for identifying components that are critical for the equipment operation. This is done by ranking the components based on the severity of their failure effects. Each type of failure effect is given a severity number (S) from 1 to 10, and components having a severity number higher than 6 are termed to be critical. The MTTF and MTTR of these critical components are used in the simulation model for calculating TMLT and TMC of the

Table 7: Severity Ranking Guideline

Rank	Severity Class	Description
7-10	Critical	Failure results in major breakdown
4-6	Major	Failure results in low level system damage
1-3	Minor	Failure results in minor system damage

equipment. Table 7 provides a guideline for ranking the components based on the severity of the failure.

3.2 Simulation

In this phase, the process for which the maintenance strategy has to be selected is simulated under two different maintenance scenarios for calculating the TMLT and MMC of the individual equipment. In the first scenario, the various equipment is simulated under PM and in the second scenario the equipment are simulated under PdM. The output from the simulation is then used to analyze the effect of TMLT and TMC on the overall profit. Figure 7 shows the input and output of phase 2.

Two simulation models are constructed in ARENA® 10.0 for simulating the process. One model is used for analyzing the equipment under preventive maintenance and the second model is used for predictive maintenance. In both the models parts are programmed to arrive in the system based on their inter-arrival distribution. The processing time of the equipment, quantity of spare parts ordered and the total simulation time are same in both the models. The models differ in the time at which maintenance is performed on the equipment and the time taken to perform the maintenance. The

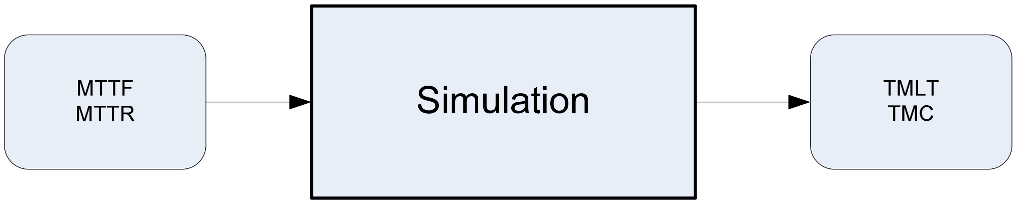

Figure 7: Phase 2

simulation models are described in Appendix 1. The following section illustrates the two scenarios that are considered for calculating TMLT and TMC.

3.2.1 Scenario 1: Determining TMLT and TMC under PM

Most manufacturers perform PM on a scheduled basis on all the equipment irrespective of its condition. Though this practice may reduce the potential effects of the equipment failure, performing maintenance when not needed will reduce equipment availability and increase maintenance cost. However, determining the optimal maintenance schedule is a challenge that most manufacturers face. In order to overcome this problem, an empirical approach is followed to calculate the TMLT and TMC of the equipment under PM. In this scenario, every time maintenance is performed the simulation model is programmed to calculate the TMLT of the equipment as a summation of the mean time taken to repair all the components. The steps involved in calculating the TMLT and TMC of the equipment under PM are

Step 1: For each equipment, identify the component that has the highest severity rank.

Step 2: Among the identified critical components, select the component that has the lowest MTTF. This is denoted as A.

Step 3: Using the MTTF of the identified component as the PM schedule, simulate the system to determine the TMLT and TMC of the equipment.

- ❖ The inputs for the PM simulation model are;

1. MTTF of all the components (In this case, the MTTF selected in Step 3 will be used as the MTTF for all the components)
2. MTTR of all the components
3. Quantity of spare parts ordered
4. Rate of Interest for holding the spare parts
5. Spare parts cost
6. Cost of labor per hour
7. Total simulation time which is the total operating time
8. Total number of simulation runs

- ❖ The outputs of the PM simulation model are;

1. TMLT
2. TMC

3.2.2 Scenario 2: Determining TMLT and TMC under PdM

By definition, PdM monitors the equipment condition continuously and initiates maintenance activities only when the condition deteriorates. Due to the lack of information regarding the equipment condition prior to the implementation of PdM, it is not possible to determine the exact failure time of the equipment. A probable solution to this problem is to calculate TMLT and TMC at different failure levels of the component. In order to determine the failure levels, a 95% confidence interval is constructed on the failure times of the critical components and the Upper 95% Confidence Limit (UCL), Lower 95% Confidence Limit (LCL) and the Mean Level (ML) are selected as the three MTTF levels of component failures. The system is then simulated under these three levels of MTTF to calculate the TMLT and TMC of each equipment. In this scenario, every time maintenance is performed the simulation model is programmed to calculate the mean time taken to repair the critical and non-critical components separately. TMC is calculated based on the MTTR of the critical and non-critical components. However, equipment availability is calculated based on the MTTR of the critical components only as it is assumed that the non-critical components are maintained while the equipment are under operation. The steps involved in calculating the TMLT and TMC of the equipment under PdM are

Step 1: For each equipment, identify the components that have a severity rank of more than 6.

Step 2: Construct a 95% CI on the failure times of the identified critical components.

Step 3: Select the values at the Upper 95% CI , Mean CI and the Lower 95 CI as the three levels of MTTF.

Step 4: Denote these three levels as Level UCL, ML and LCL respectively.

Step 5: Using levels UCL, ML and LCL as the equipment failure time, simulate the system to determine the TMLT and TMC of the equipment.

- The inputs for the PdM simulation model are;

  1. MTTF of all the components
  2. MTTR of all the components
  3. Quantity of spare parts ordered
  4. Rate of Interest for holding the spare parts
  5. Spare parts cost
  6. Cost of labor per hour
  7. Cost of condition monitoring equipment
  8. Total simulation time which is the total operating time
  9. Total number of simulation runs

- The outputs of the PdM simulation model are;

  1. TMLT
  2. TMC

3.2.3 Analysis of Simulation Results

In this stage, TMLT and TMC calculated from simulation are used for analyzing its effect on the overall profit. The TMLT and TMC calculated from preventive maintenance are grouped into one set and the values from predictive maintenance are grouped into another set. The elements from the two sets are cross mapped and its effect on the profit is analyzed. In order to analyze the effect of different levels of TMLT and TMC on the overall profit, a permutation design is formulated. The main objective of the permutation is to formulate a design of all the possible mapping combination of TMLT and TMC calculated at different failure levels and analyze the effect of the combinations on the organizational profit.

Permutation Design Formulation

Response Variable: Overall Profit

Factors: TMLT, TMC

PM Levels: A

PdM Levels: UCL, ML, LCL

3.3 Profit Calculation

Figure 8 shows the input and output of phase 3. In this phase, a deterministic model developed in Microsoft Excel is used for profit calculation. Equation 1 shows the mathematical formula used for calculating the profit. The profit associated with each permutation combination is determined under all the strategies. The calculated profits are then used for performing a statistical analysis.

Assumptions:

1. Machines are independent and every machine can produce only one type of product.
2. The same product cannot be produced by more than one machine

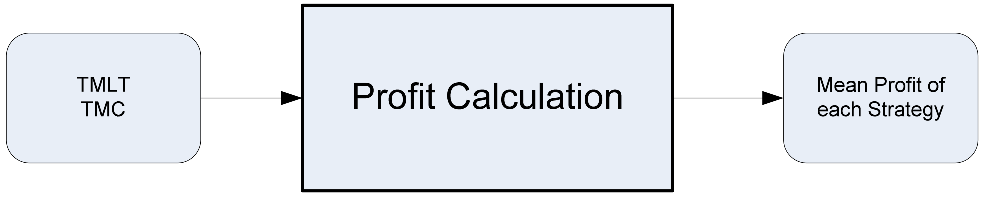

Figure 8: Phase 3

3. The total operating time of machines includes the daily breaks

$$\text{Profit} = \sum_{j=1}^{m}\sum_{i=1}^{n}\left[(Sc_i - Pc_i)*(AT_j * C_j)\right] - \sum_{i=1}^{n}(Pc_i * X_i) - \sum_{j=1}^{m} TMC_j \quad \_\_\_\_\_\_ (1)$$

Where,

$$AT_j = TOT_j - TMT_j \quad \text{for all j} \quad \_\_\_\_\_\_ (2)$$

$$TMT_j = N * MTTR_j \quad \text{for all j} \quad \_\_\_\_\_\_ (3)$$

$$TMC_j = LC_j + SPC_j + IHC_j + EC_j \quad \text{for all j} \quad \_\_\_\_\_\_ (4)$$

Notations

i = an index of product types, i= 1,...,n where n represents total number of product types

j = an index of machines, j= 1,...,m where m represents total number of machines

Sc_i = Selling Cost of one unit of product i

Pc_i = Production Cost of one unit of product i

AT_j = Total time machine j is available for production

C_j = Amount of product i produced by machine j in one unit time

X_i = Permissible quantity of scrap for product i

TMC_j =Total Maintenance Cost of machine j

TOT_j = Total operating time of machine j

TMT_j = Total maintenance time of machine j producing product i

N = Number of times maintenance is performed

$MTTR_j$ = Mean time to repair machine j producing product i

LC_j = Labor Cost involved in repairing machine j

SPC_j = Cost of machine j spare parts

IHC_j = Cost of holding machine j spare parts inventory

EC_j = Cost associated with the auxiliary equipment used for monitoring the condition of equipment j

3.3.1 Statistical Analysis

In this phase, the statistical significance of strategies is tested by performing an Analysis of Variance (ANOVA) on the profit means associated with each strategy at 95% confidence interval. The F-test within the ANOVA is used for this purpose. A small p-value of the F-test rejects the null hypothesis that the profit means of the strategies are equal thereby confirming that the profit means associated with each strategy are statistically different.

3.4 Strategy Selection

In this phase a comparative analysis is performed on the mean profits calculated under each strategy and the variation associated with the profits is assessed.

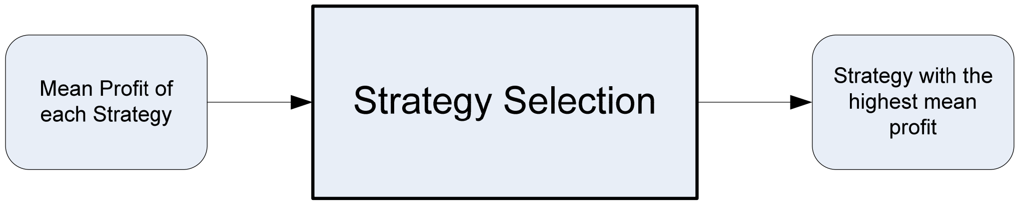

Figure 9: Phase 4

Figure 9 shows the input and output of phase 4. Mean Square Deviation (MSD) test is used for this purpose. A low MSD value explains minimal variation in the profits. Hence the strategy with the lowest MSD value is selected as the best maintenance strategy. Equation 5 represents the formula for calculating MSD where MSD is the mean-square deviation, s_i is the standard deviation of the *ith* strategy, c_i is the mean of the *ith* strategy and c_{max} is the mean of the strategy that gives the highest profit.

$$MSD = s^2{}_i + (c_i - c_{\max})^2 \qquad (5)$$

3.5 Validation

3.5.1 Strategy Validation

Figure 10 shows the input and output of phase 5. In this stage the selected strategy is validated by simulating the system under the selected strategy and comparing the process metrics with the existing strategy.

Figure 10: Phase 5

The parameters that are used for validating the strategy are

1. Total Number of Products Produced
2. Work in Process Inventory
3. Spare Parts Inventory
4. Inventory Holding Cost
5. Total Maintenance Lead Time
6. Total Maintenance Cost
7. Overall Profit

3.5.2 Model Validation

In this stage the ELMSS model is validated by comparing its features against the features of the existing maintenance strategy selection models.

3.6 Steps Involved in the Methodology

Step 1: Identifying Equipment

In this step the equipment for which the maintenance strategy has to be selected is determined.

Step 2: Identifying Critical Components

In this step the components that are critical for the equipment operation are determined.

Step 3: Calculating TMLT and TMC

In this step the values of TMLT and TMC at different levels of preventive and predictive maintenance are calculated

Step 4: Determining all possible strategy combinations

In this step all the different possible maintenance strategies are determined. This depends upon the number of machines selected. Based on the number of machines selected in the previous step the possible number of strategy combinations will be n^r where 'n' represents the number of maintenance types that is being considered.

Step 5: Formulating a Permutation Design

In this step a permutation design is formulated for the equipment using the values of TMLT and TMC obtained from simulation.

Step 6: Calculating Strategy Profits

In this step, the profit associated with different combinations of levels is calculated under each strategy.

Step 7: Analyzing the Significance of the Strategies

In this step the statistical significance of the calculated profits is tested.

Step 8: Selecting the Final Strategy

In this step the strategy with the highest profit and minimum variation is selected as the best strategy.

Step 9: Validating the ELMSS Model

In this step the selected strategy and the ELMSS model are validated.

Figure 11 shows the overall methodology involved in selecting the maintenance strategy using the ELMSS model.

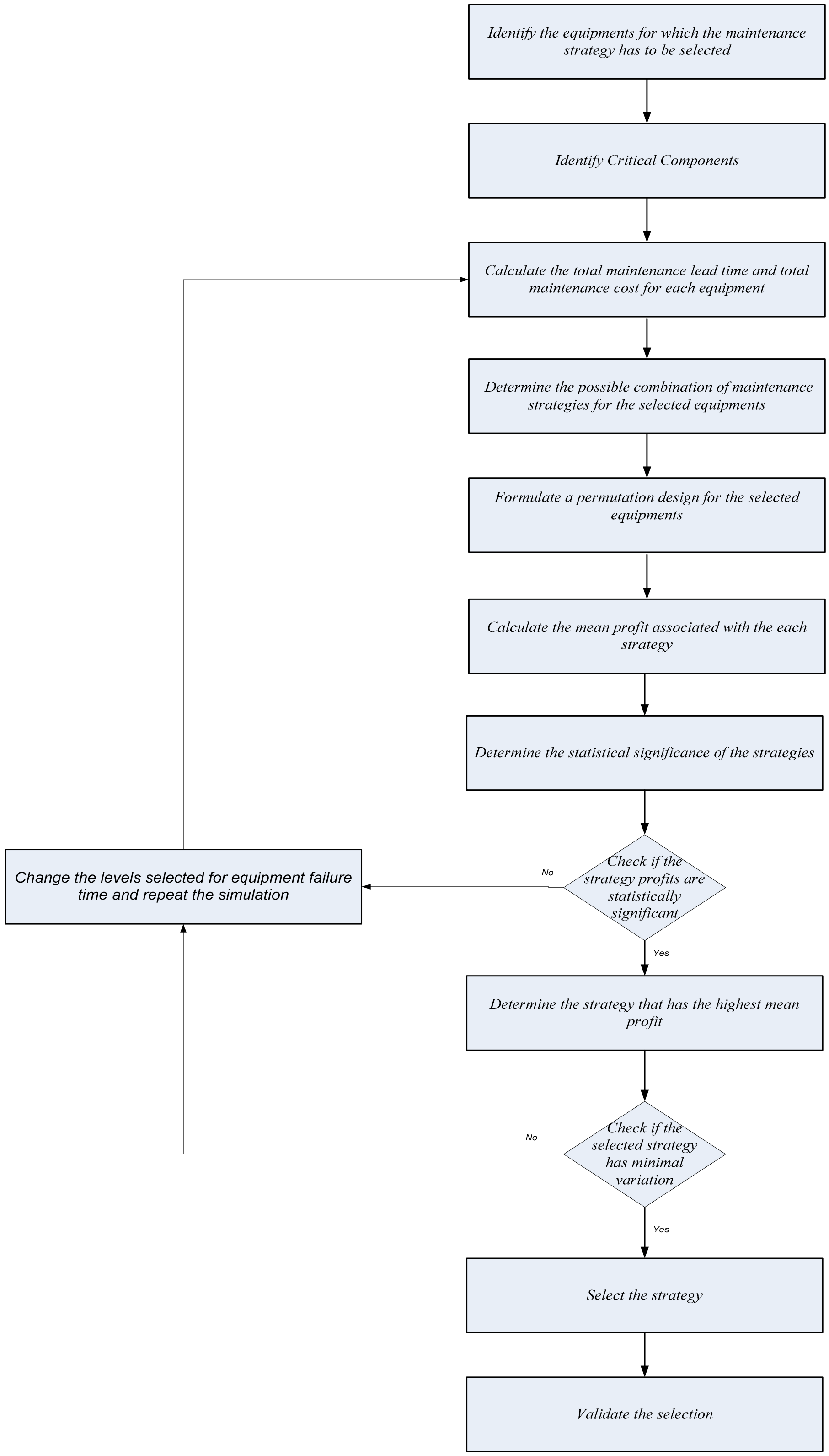

Figure 11: Maintenance Strategy Selection Methodology

Chapter 4

Case Study and Results

Chapter 4 illustrates the ELMMS model for selecting the maintenance strategy using an industry case study.

4.1 Case Study

A metal tubing manufacturer was selected as a case study for illustrating the application of the model. The manufacturing process consists of three individual operations, namely Cutting, Bending and Welding. Each operation is performed by individual equipment and the products manufactured are non identical. The process parameters of the equipment are given in Table 8. The ELMSS model is then used to determine the best maintenance strategy that will maximize the organizational profit.

Table 8: Process Parameters

	Cutting	Bending	Welding
Selling Cost ($)	**30**	**95**	**75**
Production Cost ($)	**25**	**85**	**70**
Capacity (parts/hour)	**5**	**1**	**2**
Total Operating Hours	**5840**	**5840**	**5840**
Permissible Scrap (parts)	**300**	**100**	**250**
Cost /Part ($)	**100**	**500**	**300**
Equipment Cost ($)	**5000**	**8000**	**6000**
Labor Cost ($/hour)	**15**	**15**	**15**

Phase 1: FMECA

Step 1: *Identifying Equipment*

The equipment for which the maintenance strategy has to be selected are identified to be Cutting, Bending and Welding

Step 2: Identifying Critical Components

Tables 9, 10 and 11 provide a summary of the modified FMECA performed on the equipment. From the tables, it can be determined that Motor 1 and 2 are the critical equipment for Cutting equipment, Hydraulic Motor, Pressure Pump and Lift Motor are critical for Bending and the Welding Electrode 2 is critical for the Welding equipment. The MTTF and MTTR of the components are then calculated by identifying the failure time and repair distributions and calculating the mean value of the respective distributions. It was observed that the MTTF and MTTR of all the components followed Weibull and Normal distributions respectively. The failure and repair time data of the equipment components is given in Appendix 2.

Table 9: Modified FMECA for Cutting Equipment

Component	**Function**	**Failure Cause**	**Potential Effects**	**Severity**	**MTTF (Hours)**	**MTTR (Hours)**
Motor 1 (C1)	Operates the saw	Over heating	Parts cannot be cut	10	1440	50
Conveyor Motor (C2)	Moves the parts	Over heating	Parts cannot be moved	6	480	20
Motor 2 (C3)	Operates the saw handle	Over heating	Parts cannot be cut	10	960	35

Table 10: Modified FMECA for Bending Equipment

Component	Function	Failure Cause	Potential Effects	Severity	MTTF (Hours)	MTTR (Hours)
Hydraulic Motor (B1)	Bends the tube	Vibration	Dimensional instability	9	960	40
Pressure Pump (B2)	Supplies the pressure for bending	Leak	Component damage	9	1440	20
Lift Motor (B3)	Removes the finished part from the equipment	Vibration	Component damage	7	800	30

Phase 2: Simulation

Step 3: Calculating TMLT and TMC

In this step, the maintenance schedule of preventive and predictive maintenance is first determined. The TMLT and TMC associated with each maintenance technique are then calculated by simulating the process under the respective MTTF. Simulation was

Table 11: Modified FMECA for Welding Equipment

Component	Function	Failure Cause	Potential Effects	Severity	MTTF (Hours)	MTTR (Hours)
Welding Electrode 1 (W1)	Welds Part	Insufficient flux	Weak Joint	4	800	25
Welding Electrode 2 (W2)	Welds Parts	Insufficient welding material deposition	Weak Joint	9	960	15
Work piece (W3)	To adhere to the mating part	Insufficient thickness/weld area	Weak Joint	2	480	5

Table 12: Results from Simulation under PM

	Cutting	Bending	Welding
MTTF (hours)	720	720	720
TMLT (hours)	840	630	420
TMC ($)	58770	51356	50844

run for 365 days considering that the total operating time per day was 16 hours (2 shifts, 8 hour per shift). The number of simulation replications was determined by trial and error method until the results had reasonable statistical confidence. It was observed that TMLT and TMC had sufficient statistical confidence when the model was simulated for 10 replications. Table 12 and 13 gives the MTTF and the corresponding TMLT and TMC determined from 10 simulation replications.

Table 13: Results from Simulation under PdM

	Cutting			**Bending**			**Welding**		
	LCL	**ML**	**UCL**	**LCL**	**ML**	**UCL**	**LCL**	**ML**	**UCL**
MTTF (hours)	656	960	1263	547	800	1052	656	960	1263
TMLT (hours)	575	455	320	440	325	240	305	230	160
TMC ($)	85224	56258	100887	96356	78000	106915	59618	54614	62424

Phase 3: Permutation

Step 4: Determining all Possible Strategy Combinations

The total number of possible strategy combinations is $2^3 = 8$, where ‘2’ refers to the number of maintenance alternatives and ‘3’ refers to the number of equipment. Table 14 shows all the possible combinations.

Step 5: Formulating a Permutation Design

In this step the TMLT and TMC calculated at different levels of MTTF are used for formulating a permutation design. Table 15 and 16 show the permutation design formulated for the selected equipment.

Table 14: Maintenance Strategies

	Cutting	Bending	Welding
Strategy 1	**Preventive**	**Preventive**	**Preventive**
Strategy 2	**Preventive**	**Preventive**	**Predictive**
Strategy 3	**Preventive**	**Predictive**	**Preventive**
Strategy 4	**Preventive**	**Predictive**	**Predictive**
Strategy 5	**Predictive**	**Preventive**	**Preventive**
Strategy 6	**Predictive**	**Preventive**	**Predictive**
Strategy 7	**Predictive**	**Predictive**	**Preventive**
Strategy 8	**Predictive**	**Predictive**	**Predictive**

Table 15: Permutation Design of Strategies 1 to 4

Strategy 1			Strategy 2			Strategy 3			Strategy 4		
Cutting (Hours)	Bending (Hours)	Welding (Hours)	Cutting (Hours)	Bending (Hours)	Welding (Hours)	Cutting (Hours)	Bending (Hours)	Welding (Hours)	Cutting (Hours)	Bending (Hours)	Welding (Hours)
720	720	720	720	720	656	720	547	720	720	547	656
720	720	720	720	720	960	720	547	720	720	547	960
720	720	720	720	720	1263	720	547	720	720	547	1263
720	720	720	720	720	656	720	800	720	720	800	656
720	720	720	720	720	960	720	800	720	720	800	960
720	720	720	720	720	1263	720	800	720	720	800	1263
720	720	720	720	720	656	720	1052	720	720	1052	656
720	720	720	720	720	960	720	1052	720	720	1052	960
720	720	720	720	720	1263	720	1052	720	720	1052	1263
720	720	720	720	720	656	720	547	720	720	547	656
720	720	720	720	720	960	720	547	720	720	547	960
720	720	720	720	720	1263	720	547	720	720	547	1263
720	720	720	720	720	656	720	800	720	720	800	656
720	720	720	720	720	960	720	800	720	720	800	960
720	720	720	720	720	1263	720	800	720	720	800	1263
720	720	720	720	720	656	720	1052	720	720	1052	656
720	720	720	720	720	960	720	1052	720	720	1052	960
720	720	720	720	720	1263	720	1052	720	720	1052	1263
720	720	720	720	720	656	720	547	720	720	547	656
720	720	720	720	720	960	720	547	720	720	547	960
720	720	720	720	720	1263	720	547	720	720	547	1263
720	720	720	720	720	656	720	800	720	720	800	656
720	720	720	720	720	960	720	800	720	720	800	960
720	720	720	720	720	1263	720	800	720	720	800	1263
720	720	720	720	720	656	720	1052	720	720	1052	656
720	720	720	720	720	960	720	1052	720	720	1052	960
720	720	720	720	720	1263	720	1052	720	720	1052	1263

Table 16: Permutation Design of Strategies 5 to 8

Strategy 5			Strategy 6			Strategy 7			Strategy 8		
Cutting (Hours)	Bending (Hours)	Welding (Hours)	Cutting (Hours)	Bending (Hours)	Welding (Hours)	Cutting (Hours)	Bending (Hours)	Welding (Hours)	Cutting (Hours)	Bending (Hours)	Welding (Hours)
656	720	720	656	720	656	656	547	720	656	547	656
656	720	720	656	720	960	656	547	720	656	547	960
656	720	720	656	720	1263	656	547	720	656	547	1263
656	720	720	656	720	656	656	800	720	656	800	656
656	720	720	656	720	960	656	800	720	656	800	960
656	720	720	656	720	1263	656	800	720	656	800	1263
656	720	720	656	720	656	656	1052	720	656	1052	656
656	720	720	656	720	960	656	1052	720	656	1052	960
656	720	720	960	720	1263	960	1052	720	960	1052	1263
960	720	720	960	720	656	960	547	720	960	547	656
960	720	720	960	720	960	960	547	720	960	547	960
960	720	720	960	720	1263	960	547	720	960	547	1263
960	720	720	960	720	656	960	800	720	960	800	656
960	720	720	960	720	960	960	800	720	960	800	960
960	720	720	960	720	1263	960	800	720	960	800	1263
960	720	720	960	720	656	960	1052	720	960	1052	656
960	720	720	960	720	960	960	1052	720	960	1052	960
960	720	720	1263	720	1263	1263	1052	720	1263	1052	1263
1263	720	720	1263	720	656	1263	547	720	1263	547	656
1263	720	720	1263	720	960	1263	547	720	1263	547	960
1263	720	720	1263	720	1263	1263	547	720	1263	547	1263
1263	720	720	1263	720	656	1263	800	720	1263	800	656
1263	720	720	1263	720	960	1263	800	720	1263	800	960
1263	720	720	1263	720	1263	1263	800	720	1263	800	1263
1263	720	720	1263	720	656	1263	1052	720	1263	1052	656
1263	720	720	1263	720	960	1263	1052	720	1263	1052	960
1263	720	720	720	720	1263	720	1052	720	720	1052	1263

Phase 4: Profit Calculation

Step 6: Calculating Organizational Profit

In this step profit associated with each combination is calculated and the average profit associated with each strategy is determined. Table 17 the profit calculated for each combination.

Phase 5: Statistical Analysis

Step 7: Analyzing the Statistical Significance of the Profits

In this step, an ANOVA is performed on the average profits calculated under each strategy to test if the profits calculated under the strategies are significantly different from each other. Table 18 shows the results of ANOVA performed on the profit means at 95% significance level. The p value of the F test is very significant thereby rejecting the null hypothesis that the profit means of the strategies are equal. Thus it can be concluded that the profit means associated with each strategy are statistically different.

Table 17: Strategy Profits

Strategy	**Profit**
1	$80,880.00
2	$63,274.33
3	$88,135.67
4	$70,530.00
5	$100,350.33
6	$82,744.67
7	$107,606.00
8	$90,000.33

Table 18: ANOVA Results

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.0052E+10	7	5721670885	50.2515974	<0.0005	2.0538082
Within Groups	2.3683E+10	208	113860478			
Total	6.3735E+10	215				

Phase 6: Strategy Selection

Step 8: Selecting the Final Strategy

In this phase the variation associated with calculated profits is assessed and the strategy that has the minimum variation is selected as the best strategy. Tables 19 shows the MSD values calculated for the eight strategies at three different PM schedule.

From the above table it can be concluded that the best option to maximize organizational profit is to implement PdM for Cutting and Bending and PM for Welding equipment (Strategy 7). The choice of this strategy is validated in the next phase.

Table 19: Mean Profits

Strategy	Profit	MSD
1	$80,880.00	7.14E+08
2	$63,274.33	2.1E+09
3	$88,135.67	3.94E+08
4	$70,530.00	1.53E+09
5	$100,350.33	1.27E+08
6	$82,744.67	8.31E+08
7	$107,606.00	8.9E+07
8	$90,000.33	5.38E+08

Phase 7: Validation

Step 9: Validating the ELMSS Model

In this phase the equipment are simulated under the selected maintenance strategy and the resulting process metrics are compared with the existing metrics. Table 20 shows a comparison of the process metrics obtained from the existing and selected strategy. It can be confirmed from the table that the selected maintenance strategy performs better than the existing strategy thus validating the ELMSS model.

Table 21 shows a comparison of the ideal features that different maintenance strategy selection model possess and indicates the strengths and weaknesses of the proposed ELMSS model.

Table 20: Validation Results

	Old Strategy (PPP)	Selected Strategy (PdPdP)
Quantity Produced	16480	18920
WIP	393	722
Spare Parts Inventory	66	45
Inventory Holding Cost	19250	16950
*P=Preventive Maintenance Pd= Predictive Maintenance		

Table 21: Model Validation

Maintenance Strategy Selection Models	Optimization	MCDM	Management	Cost Effective	Simulation	ELMSS
Ability to be used across all maintenance approaches		X				
User friendliness						X
Utilizing personnel knowledge and experience		X	X			X
Considering financial aspects adequately and consistently	X			X		X
Considering technical analysis before data gathering					X	X
Ability to consider organizational aspects			X	X		X

Ability to measure cost effectiveness				X	X	X
Flexibility (allowing feedback and continuous improvements)		X	X			X
Uncertainty in the decision making process		X				X
Time consuming	X	X	X	X	X	X
Easy to understand and interpret	X	X	X			X

Chapter 5

Conclusion

Chapter 5 summarizes the major conclusions of this thesis and gives the various merits and demerits of the methodology. Finally it discusses the opportunities for improving the model and the scope for future research in this area

5.1 Summary of Research

The main purpose of this thesis was to develop a methodology for assisting the company's management in selecting a maintenance strategy for a set of equipment that will maximize the organizational profit. The model developed in this thesis calculates overall profit based on maintenance schedule, TMLT and TMC. It provides a structured approach for calculating the maintenance metrics of the maintenance programs that the company is considering to implement in the industry. The empirical approach followed in this thesis eliminates the need for decision makers to be aware of the model dynamics. The Excel based tool developed for profit calculation eliminates any additional effort needed for the end user to make the decision. In order to get a better understanding of the work, this methodology has been applied to a metal tubing industry and the process of selecting the best maintenance strategy has been illustrated.

In precise, if a company is considering changing the current maintenance strategy this model will help the decision makers to select the best maintenance strategy by answering the following questions,

1. Which strategy has the highest profit?
2. How efficient will the equipment perform under the selected strategy?

5.2 Merits and Demerits

One of the major advantages of the methodology proposed in this thesis is the ability to analyze the system under different equipment breakdown conditions and analyze its effect on the overall profit. It can be used for selecting the maintenance strategy for infinite number of equipment. It does not require any specialized modeling knowledge for simulating the model. A major disadvantage is the lack of knowledge of the severity of the failure. Because of this it assumes that all maintenance actions involve replacement of the parts. This is an important issue with respect to maintenance cost because replacing a part when the part can be repaired and used will increase the maintenance cost. This model tries to give the best TMLT and TMC estimates of the equipment under predictive maintenance, however since predictive maintenance completely depends upon the condition of the equipment the estimated value may not always be the correct value because the condition of the equipment determine the necessary maintenance action which inurn affects the lead time and cost. Another disadvantage of the model is the inability to determine the optimal spare parts ordering quantity. Also it does not consider the inventory shortage cost for calculating the inventory cost.

5.3 Summary of Research Results with respect to Problem Statement

The objectives of this study was to

- Develop a methodology to determine the process metrics under different maintenance strategies
- Develop a mathematical model for strategy selection

- Develop a user interface platform to simplify the decision making process.

All the above objectives have been achieved through the course of this research work. The model provides a structured methodology to determine the maintenance lead times and maintenance cost of the equipment under various maintenance strategies based on the time at which maintenance is initiated. It also provides a methodology for calculating the profit based on maintenance characteristic levels and analyzing the effect of different maintenance characteristics levels on the overall profit. Finally the Excel based tool helps the decision maker to calculate and compare the profits of different strategies and also determine the best maintenance schedule that will maximize the profit.

5.4 Recommendations

Future research in this topic can be focused in combining Optimization models with the mathematical model to determine the optimal maintenance lead time, maintenance schedule and the optimal spare parts inventory that will aid in maximizing the organizational profit. Another area that could be focused is the Design of Experiments (DOE). This model analyses the effect of maintenance on overall profit by considering only the maintenance schedule, TMLT and TMC on the overall profit. More factors such as severity of the repair, wrench time, complexity of the manufacturing process, quantity of spare parts ordered and the downtime cost can also be included in profit calculation. In this case a DOE approach can be used to determine the factors that have the highest impact on the profit. Finally more number of maintenance types can be considered in the future while developing a decision making methodology.

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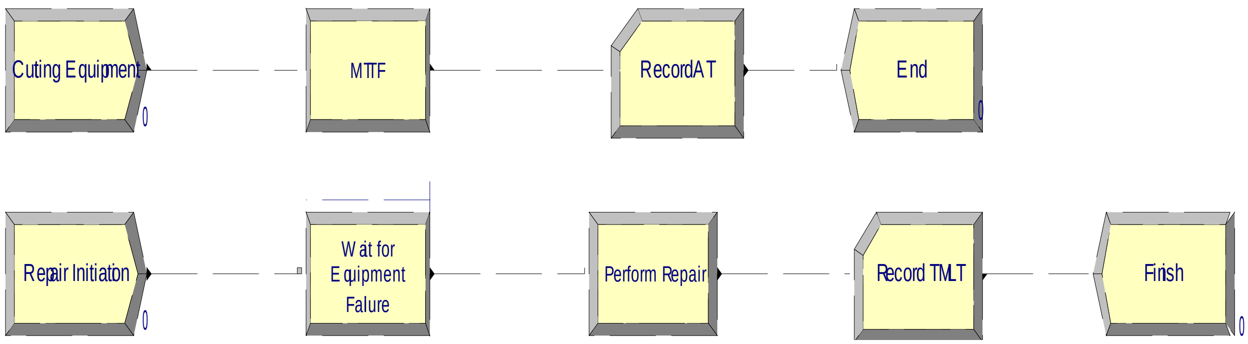
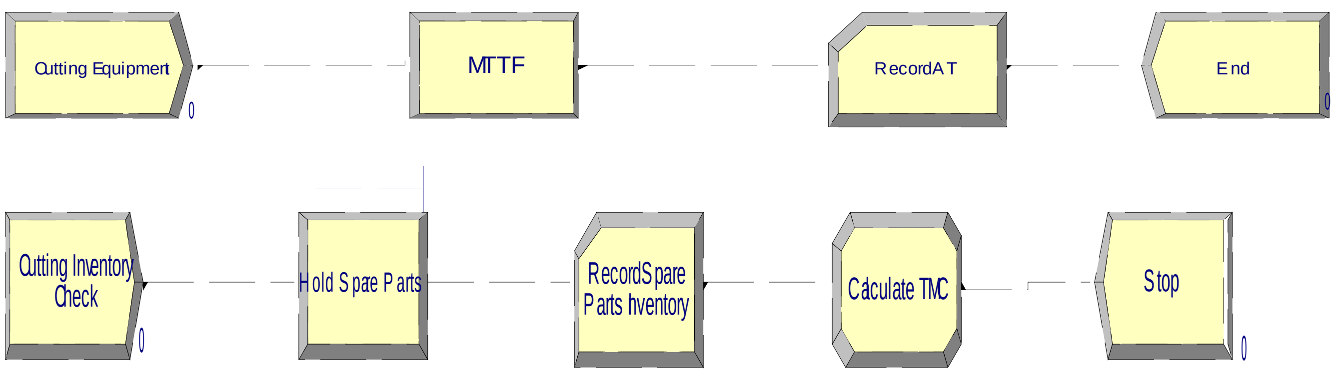
Appendix 1

Preventive Maintenance Model

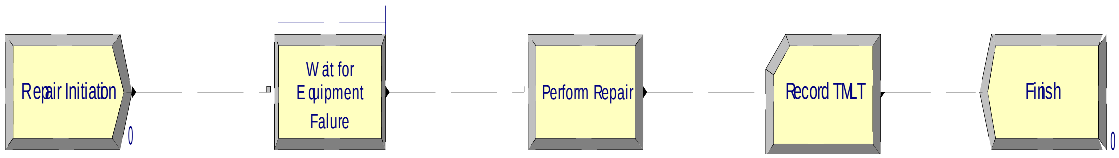
TMLT Simulation for Cutting Equipment



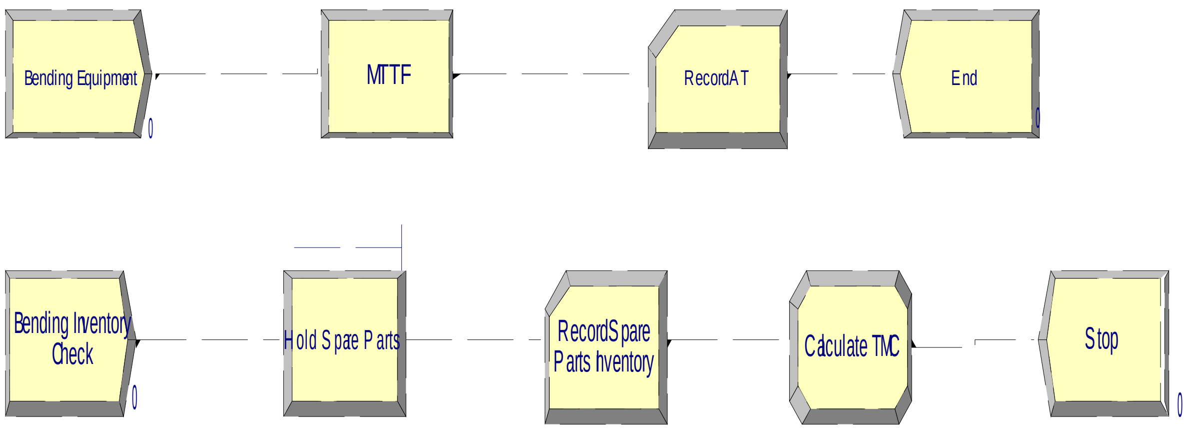
TMC Simulation Cutting Equipment



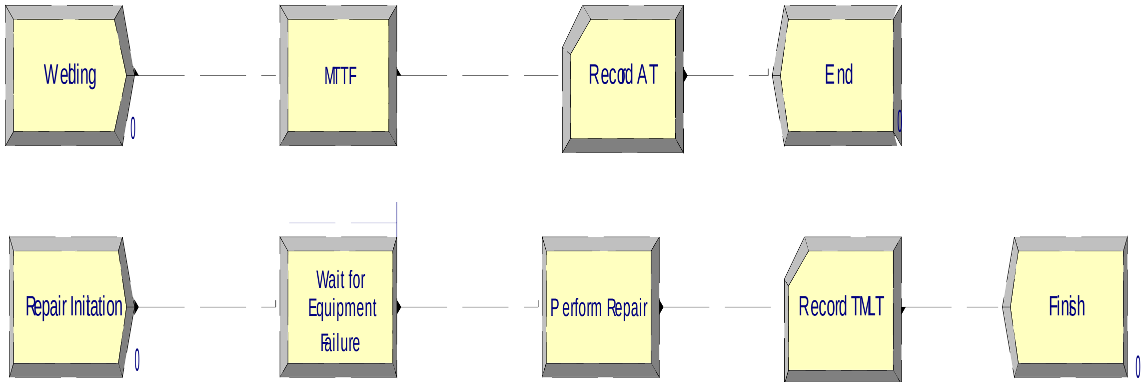
TMLT Simulation for Bending Equipment



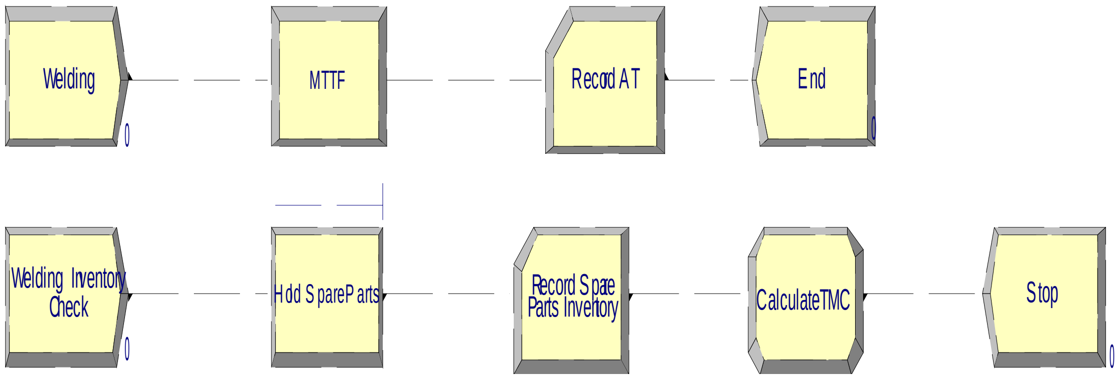
TMC Simulation for Bending Equipment



TMLT Simulation for Welding Equipment

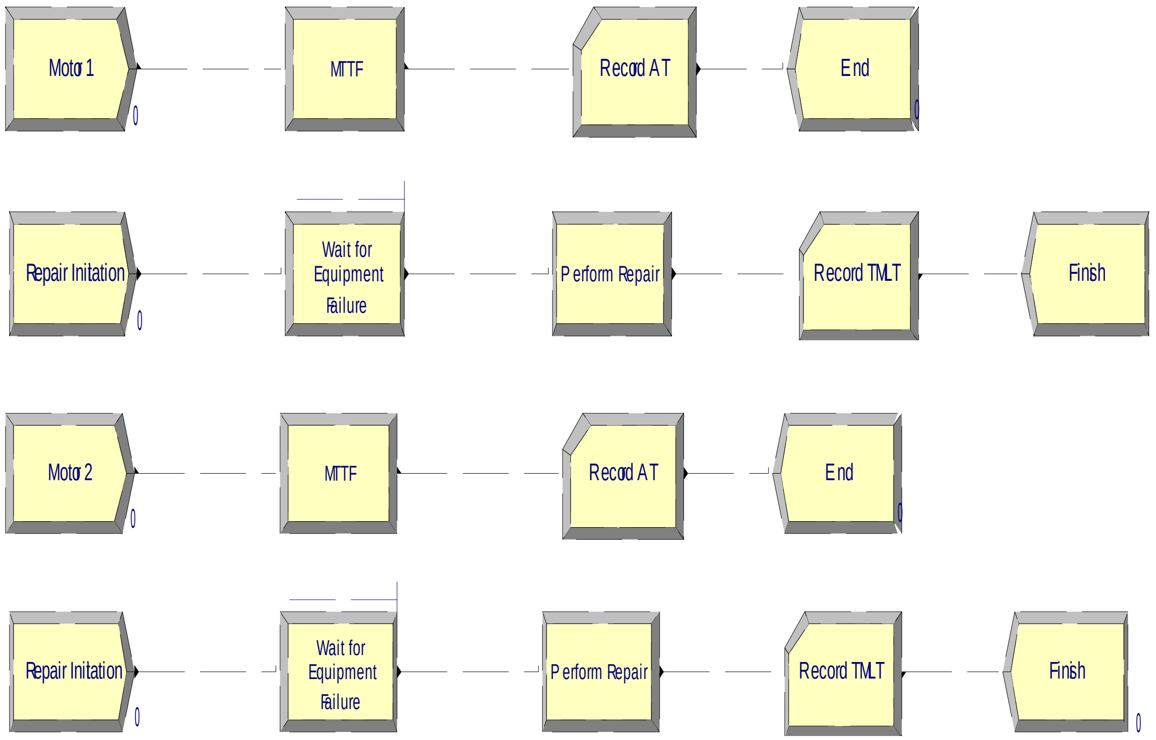


TMC Simulation for Welding Equipment

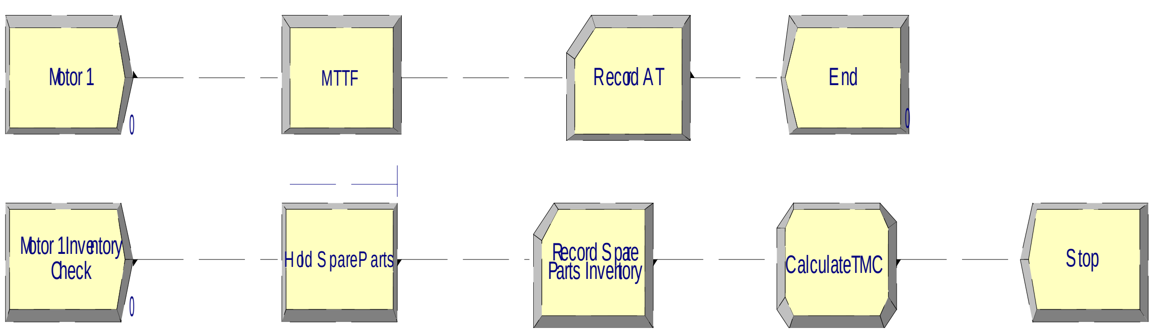


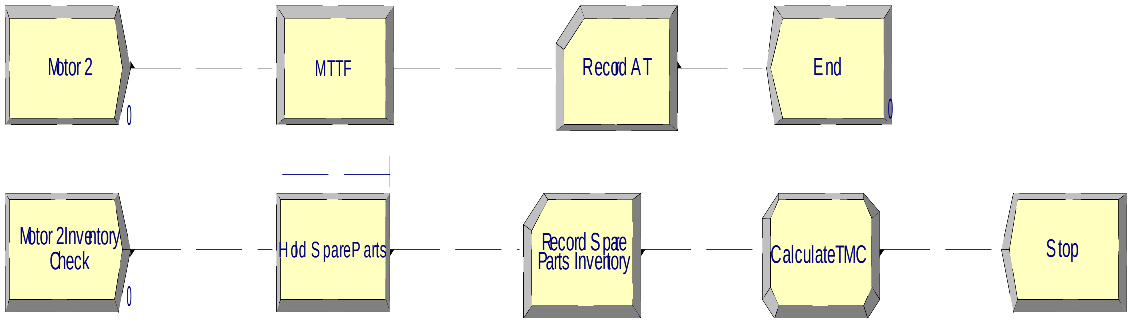
Predictive Maintenance Model

TMLT Simulation for Cutting Equipment

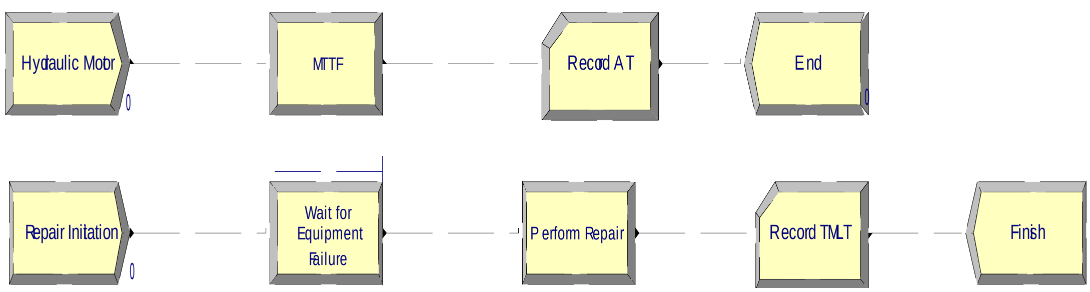


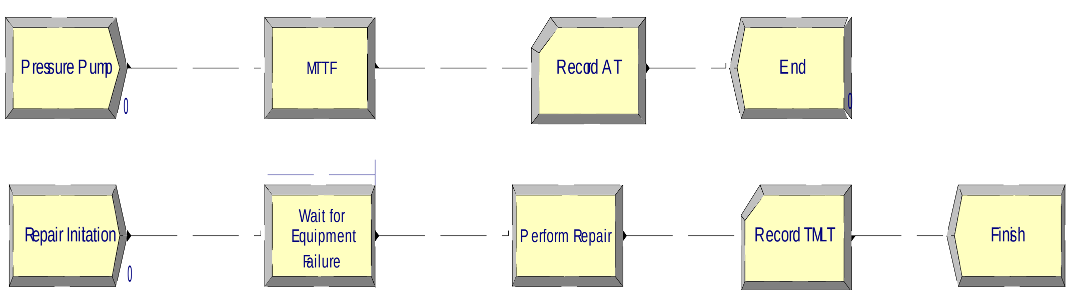
TMC Simulation for Cutting Equipment

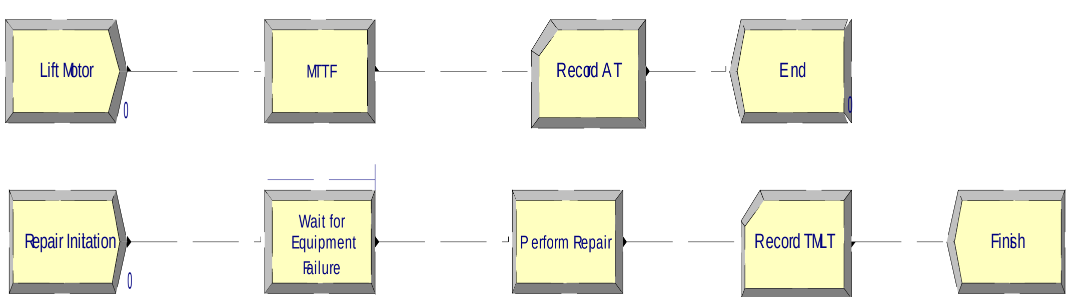




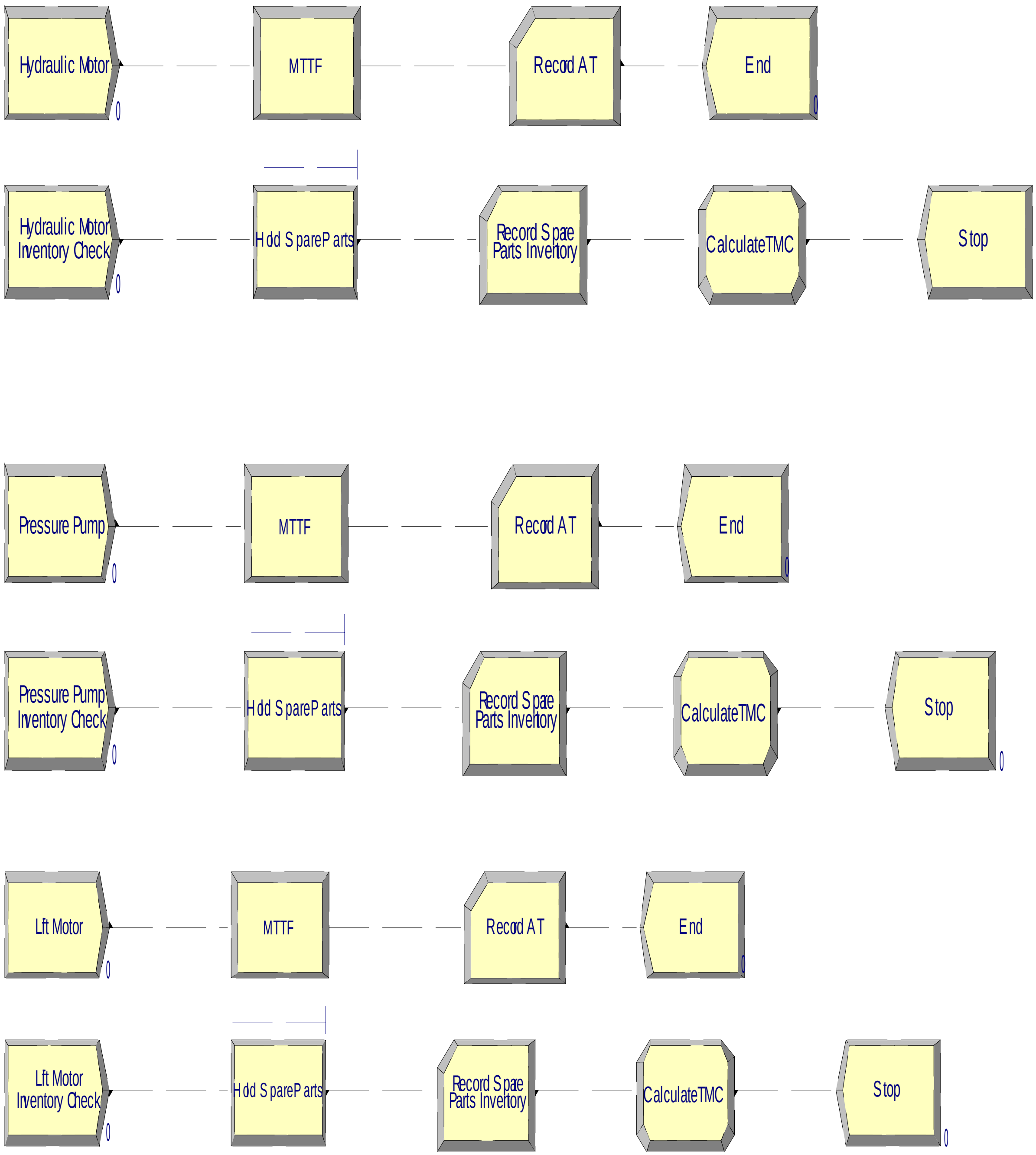
TMLT Simulation for Bending Equipment



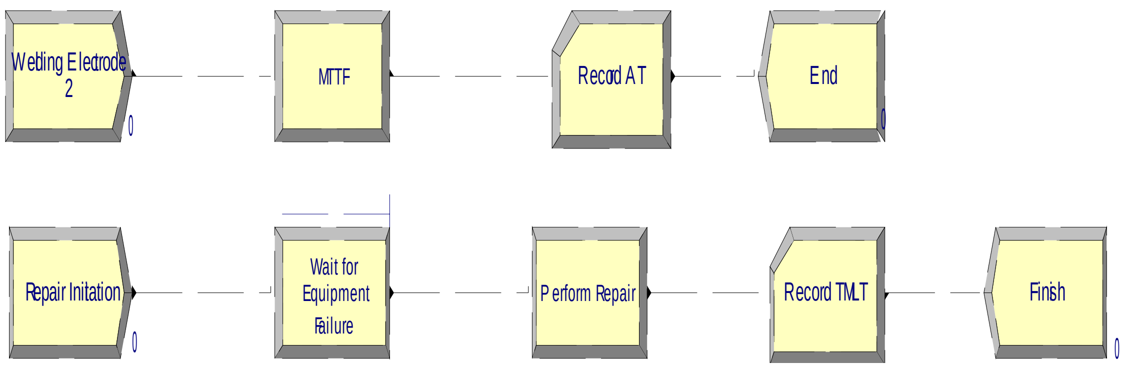




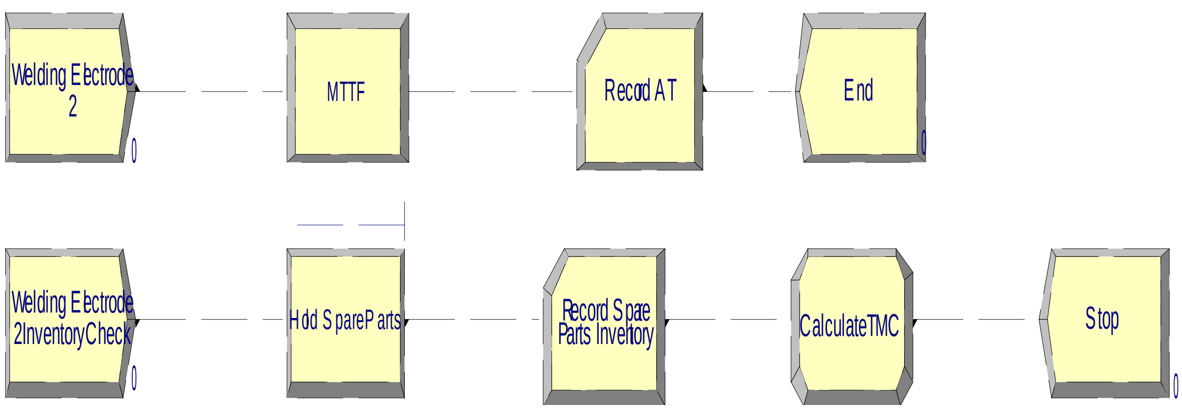
TMC Simulation for Bending Equipment



TMLT Simulation for Welding Equipment



TMC Simulation for Welding Equipment



Appendix 2

Component Failure Times

C1	C2	C3	B1	B2	B3	W1	W2	W3
1540	297	751	751	1540	759	759	751	297
639	319	925	925	639	570	570	925	319
534	199	1034	1034	534	708	708	1034	199
1565	331	609	609	1565	1172	1172	609	331
840	290	1311	1311	840	820	820	1311	290
652	263	1497	1497	652	738	738	1497	263
1342	528	944	944	1342	522	522	944	528
591	553	789	789	591	865	865	789	553
1802	456	456	456	1802	1135	1135	456	456
1441	319	469	469	1441	583	583	469	319
1372	230	336	336	1372	567	567	336	230
1025	447	390	390	1025	746	746	390	447
1319	406	1148	1148	1319	796	796	1148	406
1488	376	942	942	1488	1095	1095	942	376
1661	624	523	523	1661	910	910	523	624
1143	443	747	747	1143	1055	1055	747	443
977	230	1012	1012	977	704	704	1012	230
1299	566	1259	1259	1299	401	401	1259	566
1920	463	495	495	1920	1132	1132	495	463
1644	411	660	660	1644	1343	1343	660	411
1459	485	586	586	1459	723	723	586	485
1500	624	819	819	1500	910	910	819	624
1011	360	915	915	1011	591	591	915	360
1484	526	1120	1120	1484	728	728	1120	526
1492	552	1099	1099	1492	998	998	1099	552
1967	395	506	506	1967	467	467	506	395
1123	561	1218	1218	1123	907	907	1218	561
1210	577	804	804	1210	783	783	804	577
1410	393	790	790	1410	799	799	790	393
2014	449	909	909	2014	874	874	909	449
840	376	718	718	840	697	697	718	376
518	624	738	738	518	879	879	738	624
1705	318	936	936	1705	853	853	936	318
1589	430	523	523	1589	847	847	523	430
1155	439	1080	1080	1155	1003	1003	1080	439
1063	615	732	732	1063	464	464	732	615
873	544	941	941	873	831	831	941	544
1295	460	872	872	1295	567	567	872	460
1383	553	827	827	1383	808	808	827	553
1072	463	708	708	1072	467	467	708	463
616	234	797	797	616	770	770	797	234
1027	252	807	807	1027	669	669	807	252
977	394	844	844	977	539	539	844	394
992	210	957	957	992	1093	1093	957	210
1732	435	1026	1026	1732	675	675	1026	435
1260	589	991	991	1260	784	784	991	589
744	563	697	697	744	387	387	697	563
1558	289	906	906	1558	900	900	906	289
1201	550	851	851	1201	936	936	851	550
1512	413	417	417	1512	556	556	417	413
1459	695	950	950	1459	359	359	950	695
1883	515	854	854	1883	508	508	854	515
1175	237	660	660	1175	678	678	660	237
1294	549	535	535	1294	569	569	535	549
1191	576	474	474	1191	813	813	474	576
1139	318	669	669	1139	608	608	669	318
1123	360	862	862	1123	629	629	862	360
1454	540	663	663	1454	392	392	663	540
1755	493	513	513	1755	713	713	513	493
1180	310	984	984	1180	868	868	984	310
1379	312	678	678	1379	781	781	678	312
1352	404	877	877	1352	1080	1080	877	404
744	431	904	904	744	355	355	904	431
1972	426	678	678	1972	950	950	678	426
1158	224	1349	1349	1158	870	870	1349	224
432	550	610	610	432	746	746	610	550
1115	444	1245	1245	1115	678	678	1245	444
843	351	795	795	843	950	950	795	351
1006	523	1267	1267	1006	687	687	1267	523
1000	417	1004	1004	1000	888	888	1004	417
1417	524	1267	1267	1417	879	879	1267	524
1053	525	817	817	1053	677	677	817	525
1012	641	849	849	1012	469	469	849	641
1548	538	1182	1182	1548	494	494	1182	538
1399	483	906	906	1399	589	589	906	483
720	341	1018	1018	720	773	773	1018	341
864	203	998	998	864	420	420	998	203
1274	389	629	629	1274	880	880	629	389
1542	416	1273	1273	1542	591	591	1273	416
1719	436	814	814	1719	456	456	814	436
520	559	1239	1239	520	368	368	1239	559
1060	556	605	605	1060	830	830	605	556
1543	495	924	924	1543	1060	1060	924	495
2006	558	500	500	2006	700	700	500	558
1419	227	664	664	1419	999	999	664	227
1016	517	761	761	1016	751	751	761	517
1162	351	980	980	1162	864	864	980	351
932	476	1147	1147	932	930	930	1147	476
1717	448	543	543	1717	659	659	543	448
946	440	332	332	946	633	633	332	440
1294	574	791	791	1294	775	775	791	574
1028	349	703	703	1028	696	696	703	349
968	365	504	504	968	821	821	504	365
1232	515	1352	1352	1232	1008	1008	1352	515
1434	367	1235	1235	1434	859	859	1235	367
1361	432	1203	1203	1361	790	790	1203	432
1311	418	1236	1236	1311	865	865	1236	418
1463	340	519	519	1463	620	620	519	340
1173	418	866	866	1173	839	839	866	418
1298	391	632	632	1298	972	972	632	391

Component Repair Times

C1	C2	C3	B1	B2	B3	W1	W2	W3
53	15	32	47	22	38	23	23	5
55	26	37	35	21	46	26	26	5
43	24	27	40	18	29	22	22	5
50	16	31	41	15	22	38	38	4
57	17	34	37	11	26	12	12	4
54	20	36	43	18	21	31	31	6
46	19	30	43	24	44	33	33	6
48	21	34	43	18	23	28	28	5
40	21	37	34	18	28	25	25	2
48	25	32	37	19	36	20	20	5
58	16	38	44	12	22	25	25	3
56	14	36	40	18	33	24	24	6
46	21	34	40	27	33	27	27	7
39	31	40	41	17	31	28	28	4
44	17	40	37	24	33	27	27	5
49	25	39	44	19	23	26	26	4
45	27	29	44	19	19	28	28	4
45	19	33	36	30	25	35	35	5
54	14	20	52	25	33	32	32	6
53	26	30	36	8	33	27	27	7
47	19	40	39	21	34	21	21	5
44	16	33	31	19	41	14	14	4
48	25	41	41	11	28	25	25	6
55	23	29	35	26	32	24	24	6
58	25	20	45	24	31	30	30	4
40	14	33	41	21	36	27	27	4
47	18	32	28	21	24	16	16	5
48	10	38	28	15	15	26	26	7
45	23	31	40	26	33	25	25	5
54	24	30	45	14	34	24	24	5
49	27	37	38	16	28	28	28	4
53	12	38	37	19	37	23	23	4
56	22	35	37	20	35	18	18	4
48	24	27	40	11	33	27	27	5
51	16	33	40	21	24	31	31	5
41	22	28	38	20	30	24	24	5
52	12	40	36	20	32	29	29	6
47	15	30	28	24	27	17	17	6
49	13	30	46	16	21	16	16	4
52	17	31	29	25	25	21	21	4
45	15	39	35	21	25	30	30	3
56	24	39	43	21	30	28	28	3
48	31	28	42	10	26	22	22	4
53	22	32	39	21	34	21	21	5
51	13	42	33	19	31	31	31	4
57	26	34	40	16	35	22	22	6
59	22	39	40	15	31	32	32	5
52	24	36	45	21	34	25	25	3
54	28	39	40	22	27	26	26	3
52	14	35	32	21	34	20	20	4
46	16	32	43	6	22	25	25	5
55	17	27	40	25	30	25	25	5
44	28	40	37	23	26	24	24	4
57	23	42	38	13	32	22	22	6
44	12	36	36	20	38	22	22	5
60	25	49	45	19	36	24	24	3
54	19	35	45	19	28	34	34	5
48	20	30	43	14	40	22	22	6
54	23	27	37	15	28	15	15	5
47	18	33	37	26	28	29	29	5
53	16	33	42	24	32	28	28	5
43	22	28	48	11	40	19	19	6
49	18	42	36	13	29	27	27	6
51	20	37	45	28	26	25	25	4
40	19	30	29	13	15	29	29	4
52	31	39	37	28	30	23	23	5
52	15	30	46	20	35	22	22	3
42	23	26	32	25	28	29	29	5
51	16	37	41	19	30	18	18	5
52	21	31	42	14	36	14	14	3
53	22	32	40	21	24	22	22	3
50	27	38	41	17	45	28	28	5
51	25	36	32	23	25	26	26	4
51	12	34	42	18	34	31	31	5
52	15	32	33	24	38	33	33	3
51	17	31	31	18	31	16	16	2
37	25	33	37	12	30	20	20	5
61	17	31	39	25	38	19	19	4
44	21	31	43	20	27	29	29	3
51	27	30	43	11	33	20	20	5
50	18	36	39	22	31	32	32	5
56	25	39	34	15	26	21	21	4
51	15	25	39	25	25	25	25	5
50	18	36	28	24	32	20	20	5
52	16	34	33	13	35	25	25	4
55	18	35	35	25	27	24	24	3
46	23	33	47	25	32	23	23	5
48	17	30	35	26	31	25	25	3
47	18	33	46	24	29	24	24	5
49	17	31	44	24	28	26	26	5
53	23	32	38	23	43	23	23	4
54	18	34	30	16	17	27	27	4
39	12	44	34	15	33	20	20	6
48	5	34	40	14	25	26	26	5
45	17	25	37	19	39	17	17	3
54	14	40	35	21	31	24	24	5
50	21	39	34	23	27	27	27	4
53	23	36	40	17	37	22	22	4
48	19	35	31	24	24	29	29	5
58	28	40	47	17	30	24	24	5

Vita

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